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Hal E. Anderson

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
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ABSTRACT

Increasing expenditures for forest fire retardant and the development of more efficient delivery systems have emphasized the need for more knowledge on the transmission and retention characteristics of wildland fuels. In a series of tests, retardant was cascaded from an airplane onto arrays simulating wildland fuels. The proportion of retardant retained increased as the fuel diameter and surface roughness of individual fuel elements increased. Equations describing retention were developed and were extended to actual field situations through published research on rainfall. Retardant transmission through a tree crown was modeled; results agreed with published findings on the transmission of rain.

INTRODUCTION

The use of chemical fire retardants has increased greatly in recent years. In 1970, over 17 million gallons of fire retardants were applied from aircraft (George 1971). Increased use has intensified concern that chemical retardants be used effectively and at least cost. To help the fire manager achieve these objectives, publications such as "Chemicals for Forest Fire Fighting" (National Fire Protection Association 1967) have been published. Much research remains to be done, however, to answer questions of where to apply the chemical, in what concentration, and in what form for various fire situations and fuel types. The objective is to develop enough knowledge so the fire manager can prescribe the chemical tool needed to perform a specific job of fire control at least cost.

With the increases in technology that have occurred in recent years, delivery systems for chemical retardants are receiving increased attention. Concurrently, additional effort is needed to identify the critical fuel, location of main fire hazard, and what portion of a retardant load can be expected to be delivered to that critical fuel. The retention characteristics of the forest complex must be understood well enough to estimate the volume of retardant that will be transmitted to the critical fuel.

This paper describes the results of an investigation of the effects of fuel diameter and surface roughness upon retardant retention and provides a method for estimating retardant transmission through a tree canopy.

BACKGROUND RESEARCH

A series of tests to characterize retardants (droplet size, distribution, overall pattern, etc.) dropped by various delivery systems were started at Porterville, Calif., in 1970, and are reported by George and Blakely (1973). As a substudy to the Porterville tests, the vertical distribution of retardants within arrays of 1/2-inch wooden dowels or sandblasted aluminum tubing was determined. These tests provided the base data for the study reported in this paper.

The distribution and retention of a retardant likely derives from its rheologic properties, such as cohesiveness, adhesiveness, surface tension, and viscosity, along with the droplet size and velocity at time of impact upon fuels with specific surface characteristics, including diameter. The tests at Porterville were designed to quantitatively assess the horizontal distribution of retardant dropped by an aircraft. The retardant was dropped on a network of liquid receivers that formed a matrix of interception points. Between these interception points were placed the arrays of 1/2-inch elements that provided data on the relationship of retardant transmission through several strata of uniform elements to the nature of the element. The results are summarized by George and Blakely (1973).

The retardant retained on the element was normalized (i.e., made a fraction of the quantity of retardant reaching the ground) and measured as the average of the four adjacent grid points. The fractions passing through each vertical stratum were then summed for the fuel element type--aluminum or pine dowels. Mean values for the fractional concentrations, the portion of the original amount, and for the two types of elements were determined and are given in the following tabulation:

Element type	C_0	C_1	C_2	C_3	C_4	C_5
Aluminum	1.000	0.922	0.844	0.764	0.708	0.654
Pine dowels	1.000	.890	.793	.691	.610	.534

where:

C_0 = concentration arriving above the strata of elements

C_1 to C_5 = fraction of concentration passing through each stratum.

Linear regression equations were determined that fit these data. The equation for the 1/2-inch aluminum elements was:

$$Y = 0.980 - 1.61X, \quad r = 0.9955 \tag{1}$$

For the pine dowel, 1/2-inch elements:

$$Y = 0.972 - 2.15X, \quad r = 0.9980 \tag{2}$$

where:

Y = fraction concentration transmitted

X = element diameter × number of strata traversed

These equations describe retardant concentrations for stratum of 1/2-inch elements of the two materials, but cannot be applied to the range of fuel diameters existing in the field.

In many operational retardant drops, the retardant has significant forward velocity. Recent tests indicate the most effective ground distribution patterns are attained when the retardant is released at heights that allow dissipation of forward velocity and the formation of a true retardant cloud. Reviews of the literature on throughfall of rain for assistance in describing retardant transmission and retention generated a different concept to consider. The vertical fall of rain or retardant through a tree crown is very similar to the transmission of sunlight that is attenuated by the material through which it passes. Therefore, it should be possible to apply the principles of radiant energy transmission and attenuation to retardants and rain.

We have to assume that the material is dropping vertically and has some uniform particle distribution. In addition, the total surface area of the vegetation can capture the retardant while only the frontal area blocks sunlight or radiant energy. The attenuation of radiant energy is defined by the distance traveled through the vegetation to reduce the intensity by 63 percent and is called the mean free path. This distance can be determined from the product of the surface area-to-volume ratio, σ, of the vegetation and the packing ratio, β, of the vegetation.

The equation for the amount of retardant transmitted through a stratum would have a second component to account for the part intercepted but not retained. Various investigators have considered this as part of the drainage of the canopy, storage of the canopy, and evaporation from the vegetative surfaces (Grah and Wilson 1944; Hamilton and Rowe 1949; Raymond 1967; Rutter and others 1971). The general form of the equation for retardant transmission is:

$$C_n = C_{n-1}[e^{-\sigma\beta\ell}+D] \tag{3}$$

where:

C_n = transmitted concentration through n number of strata

C_{n-1} = concentration above the stratum, n

D = fraction not retained

σ = surface area-to-volume ratio of the fuel element, ft^2/ft^3

β = packing ratio of the fuel array, dimensionless

ℓ = distance into the strata, ft

This equation was applied to the data collected by George and Blakely, and the results for drop test No. 16 were used as an example. Since we knew the thickness of elements in the arrays (one-half inch) and their spacing, we therefore could set up the values to enter into the exponent of equation (3). The original concentration was known and the retardant retained by each layer was known, so the only component of equation (3) left to be determined was D.

Since each fuel array presented five discrete levels of fuel elements, the distance through a stratum was considered to be the thickness of the element, one-half inch (1.27 cm). With the spacings as cited by George and Blakely, the packing ratio, β, for each stratum would be 0.168. (Packing ratio is the ratio of fuel volume-to-stratum volume.) The surface area-to-volume ratio, σ, for 1/2-inch dowels is 96 ft^2/ft^3 (3.16 cm^2/cm^3). From the retardant data collected we know that only 10.5 percent of the retardant dropped was retained in the first stratum so that $C_n = 0.886$. Working with fractions we can now express the general equation (3) as:

$$D = 0.886 - \exp(-0.672) \tag{4}$$

Solving for D, we obtain a value of 0.359. This then can be substituted into the equation (3), and with the exponent values we can determine the decrease in retardant transmitted by layers. Of the retardant drops examined, drop No. 16 was selected as an example. The comparison is shown in the tabulation:

Strata	*Concentration*		*Fraction transmitted*	
	G/cm²	*Gal/100 ft²*	*Observed*	*Calculated*
0	0.123	2.8	1.000	1.000
1	.123	2.8	.895	.886
2	.123	2.8	.798	.780
3	.123	2.8	.702	.691
4	.123	2.8	.607	.610
5	.123	2.8	.516	.537

This analysis showed that only data about the first stratum are necessary to develop the information needed in equation (3). Therefore, a study was designed to investigate the effects of fuel size based upon only one stratum of elements. By including two different materials, we could gather additional information on effects of surface roughness and predict results of field application of retardants. Should retardant physical properties be altered so that very large droplets (3 to 5 cm) reach the fuel, retention predictions must consider momentum.

Since fire spreads fastest in fine fuels, the study was concentrated on retardant retention in fuels one-half inch or less in diameter. Enough information was known on certain brush species and timber types to determine size distributions 2 inches and under and to select a mean surface area-to-volume ratio for the fuel type. A literature search was conducted to accumulate the necessary vegetative information.

TEST PROCEDURES

Fire in tree crowns or on the ground generally occur in fine fuels; therefore, it was decided to make our test elements of a size range that would represent fuel diameters from branchwood down to conifer needles. Elements one-half inch, one-fourth inch, and one-eighth inch in diameter were utilized to represent branchwood dimensions. Elements of 0.057-inch nylon monofilament were used to approximate the diameter of conifer needles. (This is about twice the size of most needles [Brown 1970].) Fuel arrays were made up of one element each of the three larger fuel sizes and two elements of the needle size (fig. 1). Elements of white birch and polypyrolene plastic were selected so the effect of surface roughness on retention could be evaluated.

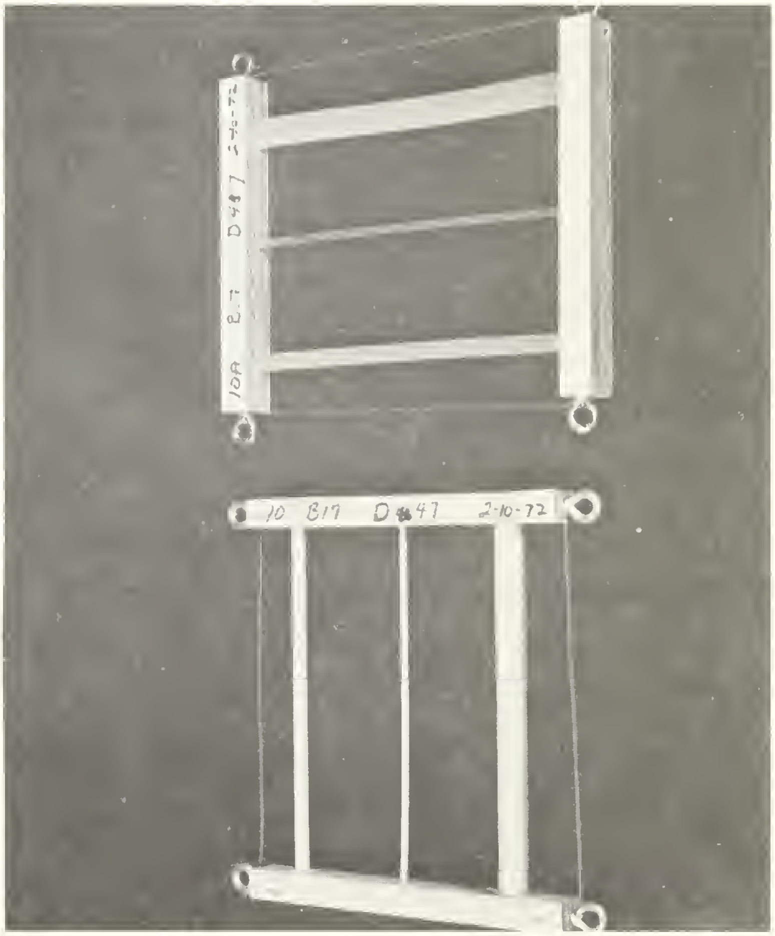

Figure 1.--Fuel arrays of polypyrolene (top) and birch (bottom) used in tests. In both arrays, two strands of monofilament (0.057 inch) represented conifer needles.

Ten arrays of each type of material were exposed to each of 10 retardant drops in the series of tests conducted at Marana, Arizona, early in 1972. The arrays were positioned along the flight line in the retardant measuring grid. Location of the arrays in the grid allowed the use of four adjacent retardant measurement points to establish the average concentration of retardant each array received. The arrays were placed in the grid prior to the drop, picked up immediately afterwards, and dried on holding racks. Arrays were then secured in transporting boxes and returned to the Fire Laboratory in Missoula, Montana.

The arrays were disassembled, the fuel elements ovendried, and gross weight determined. The retardant was then washed off and the ovendry weight redetermined to get the tare weight of the element. The difference in weight before and after drying provides the retardant weight retained by each element. Control tests were run with the white birch elements to be sure that washing did not alter weights by leaching minerals from the wood. Retardant viscosity and altitude of drop were recorded as possibly affecting retention (table 1). However, analysis of the amount of retardant on the elements as a fraction of the total delivered on a unit area basis showed no change due to retardant type or drop altitude. Therefore, the data are grouped regardless of retardant type for this series of tests.

Table 1.--*Retardant retention tests using B-17 aircraft, Marana, Ariz.*

Test No.	Drop No.	Date	Gallons dropped	Retardant type	Thickener	Tank viscosity
						Centipoise
1	3	2/1/72	500	Phos-Chek	Gum	6,300
2	6	2/2/72	500	Phos-Chek	Gum	2,300
3	8	2/2/72	500	Phos-Chek	Gum	1,700
4	10	2/2/72	500	Fire-Trol	Clay	4,900
5	15	2/3/72	500	Phos-Chek	Gum	960
6	17	2/3/72	500	Phos-Chek	Gum	1,700
7	21	2/4/72	500	Fire-Trol	Clay	1,400
8	38	2/9/72	2,000	Phos-Chek	Gum	1,675
9	47	2/10/72	500	Fire-Trol	Undiluted liquid concentration	1,900
10	51	2/10/72	500	Petro-Lite	Emulsion	>10,000

TEST RESULTS AND ANALYSIS

The concentrations of retardants within each grid point were taken from the gallons per 100 square feet (gal/100 ft^2) tabulations and equated to the measurements for the elements in g/cm^2 or lb/ft^2. Because of steep gradients in retardant concentration patterns, the amount of retardant retained by elements varied greatly within a drop. To normalize the results, weight of retardant retained by the element was divided by weight of retardant received on the ground. These values are summarized in table 2.

Table 2.--*Fractional retention of retardant by fuel size (*lb/ft^2 *total surface area ÷* lb/ft^2 *ground surface area)*

Drop No.	Polypyrolene element size (inch)				White birch element size (inch)			
	0.50	0.25	0.125	0.057	0.50	0.25	0.125	0.057[1]
3	0.350	0.361	0.313	0.339	0.260	0.302	0.460	0.406
6	.208	.376	.253	.244	1.000	.958	.625	.194
8	.316	.323	.241	.257	.936	.645	.369	.248
10	.165	.177	.238	.068	1.000	1.000	.921	.096
15	.169	.211	.141	.123	.642	.416	.220	.130
17	.186	.225	.178	.140	1.000	.991	.752	.195
21	.234	.247	.211	.077	.793	.482	.287	.121
38	.103	.123	.107	.086	.426	.138	.104	.057
47	.281	.319	.193	.088	.416	.336	.193	.125
51	.313	.357	.191	.259	1.000	.935	.480	.181
$\overline{X}$	.232	.271	.207	.168	.747	.620	.441	.175

[1] The smallest-diameter element (0.057 inch) on both white birch and polypyrolene arrays is monofilament nylon line.

The data of table 2 were subjected to Student's "t test" of the mean, and at the 99-percentile point the value of t for 18 degrees of freedom had to exceed 2.55 to indicate a significant difference between the elements. All of the elements except those of 0.057-inch diameter common to both sets of arrays had significant differences, as shown below:

Size *Inch*	*t value*
0.50	5.42
.25	3.25
.125	2.75
.057	0.22

Because the smallest size, the monofilament line, common to both arrays, had no significant difference, it is assumed that placement of the arrays on the matrix did not introduce bias and all of the data for this smallest size were lumped. Because of surface roughness, this size was considered with the polypyrolene data. The summary of the fraction retained by size, Y, is given in the following tabulation:

Element type	*Element size (inch)*			
	0.50	*0.25*	*0.125*	*0.057*
Polypyrolene	0.2324	0.2708	0.2066	0.1717
White birch	.7473	.6202	.4411	

These data were then analyzed for equations of best fit. The exponential equation found to give the closest fit for both types of elements was of the general form:

$$Y = B \exp(-A \times \sigma) \qquad (5)$$

where:

Y = the fraction retained
σ = surface area-to-volume ratio
A & B = constants

The values of the constants for the two element types and the correlation coefficient are given in equations (6) and (7):

Polypyrolene: $Y = 0.264 \exp(-5.5 \times 10^{-4} \times \sigma)$ (6)
$r = 0.8870$
White birch: $Y = 0.885 \exp(-1.83 \times 10^{-3} \times \sigma)$ (7)
$r = 0.9997$

These data, graphically presented in figure 2, show the difference in retention according to surface roughness. As the surface area-to-volume ratio approaches 900 (less than 0.125 inch in diameter), the retention capabilities fall below 0.20, and possibly merge. This suggests small-diameter fuels have about the same retention ability regardless of surface roughness.

These equations do provide a means for estimating retardant retention within fuel complexes that have mean surface area-to-volume ratios represented by these data. We assumed that the white birch curve is a good simulation for most branchwood of conifers, and the curve for polypyrolene is a good simulation for foliage and for branchwoods that have smooth surfaces or have a high oil content. To use any of these equations for determining the retardant delivered to a critical fuel, we must have detailed knowledge of the vegetative medium through which the retardant travels, including the vertical arrangements of the vegetation.

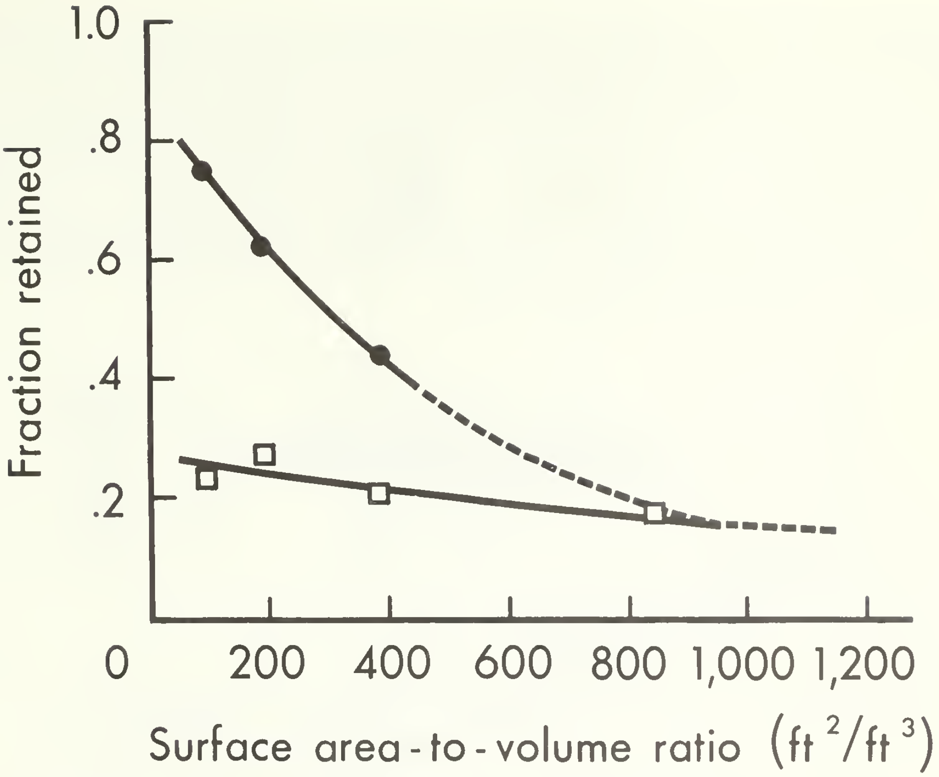

Figure 2.--Differences in retardant retention because of surface roughness (● white birch and ▪ polypyrolene) along with the influence of surface area-to-volume ratio or fuel diameter.

Information reported by George and Blakely (1973) and results of this study provide enough data to illustrate how four different surface textures affect retention. The retention factor from figure 2 for the 1/2-inch white birch applied to the packing ratio of the array used by George and Blakely indicates the retardant retained per stratum. The amount of retardant retained by one layer of 1/2-inch elements should be 0.1255. With the use of equation (3) we can arrive at values for the drip-through factor, D, as shown previously. The values for D with 1/2-inch elements can be compared for two separate tests.

It was found that the white birch and pine dowel 1/2-inch elements had approximately the same D factor, followed by aluminum tubing and polypyrolene tubing, as shown in the following tabulation:

Element type	*"D" factor*
White birch	0.3635
Pine dowels	.3789
Aluminum tubing	.4105
Polypyrolene	.4456

We can see that as surface roughness changes, the amount of retardant retained decreases, white birch being most rough and polypyrolene least rough. However, at the present time we do not have measurements to adequately describe surface roughness differences by timber types, species of vegetation, or to relate these to the test materials.

This information will see limited application until additional surface roughness data are obtained; however, the relationship of retention to roughness can be illustrated by plotting retardant transmission through a five-layered array (fig. 3). It is evident that surface roughness can change up to 1-1/2 times the quantity of retardant reaching an area. Roughness of the surface is only one of the variables affecting retardant retention. The surface materials' properties such as porosity, chemical composition, and specific gravity may have an effect. The retardant itself may have differences in cohesiveness, surface tension, density, or viscosity that significantly alter retention. However, the effort needed to obtain the information must be established by the level of use in field operations.

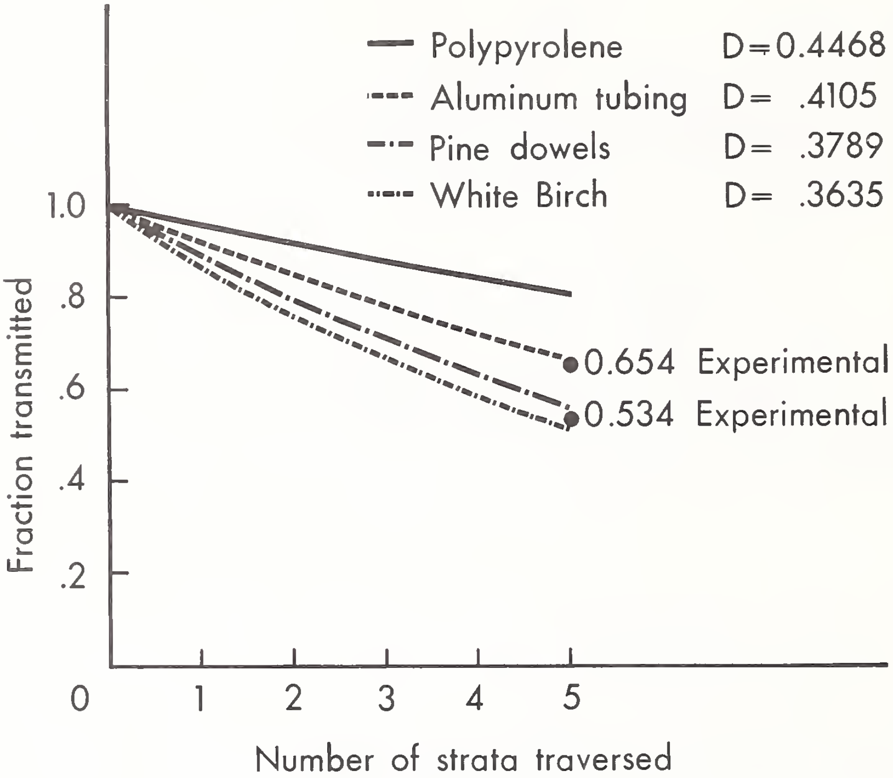

Figure 3.--Computed amounts of retardant transmitted through several layers of fuel or vegetation having different surface roughness. Fraction transmitted can be changed by the surface roughness. The experimental points show the agreement with results for pine dowels and aluminum tubing by equation (3).

APPLICATION

Efforts to develop more effective retardant delivery systems have made it mandatory that we know what portion of the retardant reaches those fuels most apt to carry fire. Assuming the fire-carrying fuel strata will be on the ground, retardant must be transmitted down through an overstory to reach those ground fuels. Because crown fuels can carry fire under specific conditions, it may also be desirable to retain as much retardant as possible in the crown material. In brushfields, the overstory shelters the understory of dead branchwood, leaf litter, and annual vegetation debris. In coniferous forests, tree canopies will shield the litter layer and brush story that may carry the fire. To estimate how much retardant needs to be delivered above a canopy, we have to determine the attenuation or retention of retardant passing through these various strata. Review of the literature shows that most investigators have considered the crown, or canopy, to be a homogeneous mixture of vegetation and branchwood.

The point of maximum fuel within the crown height has been observed and differences by species, age, or growth condition recorded (Mar:Moller 1947; Baskerville 1965; Kiil 1967; Smith 1968; Stephens 1969; Honer 1971; Moir and Francis 1972). These investigations and others provide valuable insights into the biomass distribution and other crown characteristics. To evaluate retardant transmission, however, it is necessary to know the quantity of foliage, its size and shape, the distribution of branchwood in size, and also the foliage and branchwood spatial location. Although little information has been published, we do have enough data for western conifers to indicate what can be done. The work by Storey and associates (1955) and by Fahnestock (1960) contains the information necessary to estimate the branchwood and foliage distribution within the crown. However, quantifying crown characteristics requires a geometrical shape for both the foliage and branchwood zones.

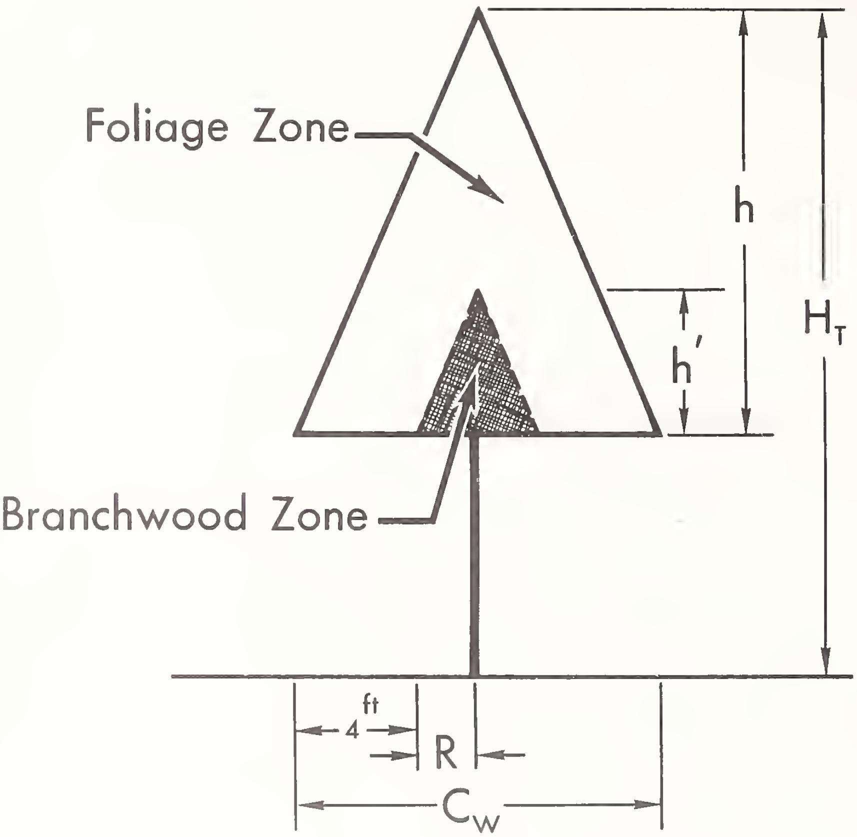

Figure 4.--Model used to develop equations describing physical properties of the crown. Symbols are defined in the text.

For the purpose of this paper we will use the data available for inland Douglas-fir and utilize the equations developed by Brickell (1968) to indicate the changes due to site and age. The configuration of a tree crown is assumed to be conical and have an outer foliage zone surrounding a branchwood zone. The foliage envelope thickness is considered to extend 4 feet horizontally and to include all foliage and all branchwood material up to one-half inch in diameter. The inner cone of branchwood is considered to contain only material greater than one-half inch in size. The general crown concept is shown in figure 4.

Having established dimensions of the tree crown, either from equations or by assumed values, we can now calculate the physical dimensions of the branchwood zone, along with the foliage zone based upon the volume of a cone. To illustrate the retardant retention equations, along with the equations describing crown envelopes, we use Brickell's inland Douglas-fir values on a site of 60 (50-year basis) at ages 20, 50, and 100 years.

$$H_T = 91.57[1 - 1.153e^{-0.0255A}]^{1.0608} = \text{tree height, ft} \qquad (8)$$

where A = age, years

$$\text{DBH} = \exp[1.317\ l_n H_T - 2.688] = \text{diameter, inches} \qquad (9)$$

These equations are used as inputs to the following equations:

$$h = 4.0 + 2.60\ \text{DBH} = \text{crown length, ft} \qquad (10)$$

$$W_c = \frac{[(\text{DBH})\ (h)]^{1.0108}}{3.811} = \text{crown weight/tree, lb/tree} \qquad (11)$$

These equations were determined by Fahnestock, or were modified by him after Storey:

$$C_w = 5.031 + 1.423(\text{DBH}) = \text{maximum crown width, ft} \qquad (12)$$

This equation is cited by Bella (1971) and is taken from data acquired by Newnham.[1] This equation may not represent inland Douglas-fir as accurately as coastal Douglas-fir.

Using the assumptions made for crown geometry, we can formulate the equations for the radius and the height of the branchwood zone.

$$R = 0.5\,C_w - 4 = \text{base radius of branchwood zone, ft} \qquad (13)$$

$$h' = \frac{(h)(R)}{0.5C_w} = \text{height of branchwood zone, ft} \qquad (14)$$

The work by Storey on western conifers provides total crown weight and the portion that is in foliage and branchwood.

$$w_f = 0.235\ W_c,\ \text{foliage weight/tree, lb} \qquad (15)$$

$$w_b = 0.765\ W_c,\ \text{branchwood weight/tree, lb} \qquad (16)$$

This information is then coupled with the work by Fahnestock to define the fraction of branchwood in the foliage zone and set up equations:

$$W_f = w_f + 0.244\ w_b = \text{foliage zone weight, lb} \qquad (17)$$

$$W_b = 0.756\ w_b = \text{branchwood zone weight, lb} \qquad (18)$$

A range of fuel diameters, or size classes, exists in both zones and retardant transmission is affected by each size class in each zone. To estimate the summed effect of size on transmission in each zone, a mean (or characteristic size of elements in each zone) is computed. This is accomplished with data on the crown weight proportioning and surface area distribution in the two zones. The data from Storey and from Fahnestock are consolidated to give the mean surface area-to-volume ratio for each size class and the portion of the total crown load that was in each class. They are as follows:

Zone	*Size class (diameter)*	*Surface area-to-volume ratio, σ*	*Fraction of crown weight*
	Inches	*Ft^2/ft^3*	
Foliage		2,100	0.235
	<1/8	770	.075
	1/8 - 1/4	256	.050
	1/4 - 1/2	128	.063
Branchwood	1/2 - 1	64	.239
	1 - 2	32	.338
	>2	18	0
			1.000

---

[1] R. M. Newnham. Unpublished thesis. University of British Columbia. 1964.

The mean surface area-to-volume ratio for the foliage zone was determined by weighting by surface area because the total surface area may be active in retaining retardant. The mean surface area-to-volume ratio of the foliage is determined by equation (19) and for the branchwood zone by equation (20).

$$\bar{\sigma}_s = \left[\frac{w_1\sigma_1}{\rho_1} + \ . \ . \ . \ + \frac{w_4\sigma_4}{\rho_4}\right] \div \left(\frac{W_c}{\bar{\rho}}\right) = \begin{array}{l}\text{mean surface-to-area} \\ \text{volume, ft}^2/\text{ft}^3 \text{ of} \\ \text{foliage zone}\end{array} \tag{19}$$

where:

w_1 . . . = fraction of crown weight in size class

W_c = crown weight

ρ_1 = density of size class

$$\bar{\sigma}_b = \left[\frac{w_5\sigma_5}{\rho_5} + \frac{w_6\sigma_6}{\rho_6}\right] \div \left(\frac{W_c}{\bar{\rho}}\right) = \begin{array}{l}\text{mean surface area-to-volume} \\ \text{of branchwood zone, ft}^2/\text{ft}^3\end{array} \tag{20}$$

The volume of each zone is then calculated, using equations for a cone:

$$V_b = 1/3\pi R^2h' = \text{branchwood zone volume, ft}^3 \tag{21}$$

$$V_F = 1/3\pi(0.5C_w)^2h = V_b = \text{foliage zone volume, ft}^3 \tag{22}$$

These equations allow us to estimate bulk densities for each zone, their volume, and the vertical distance through the zones at varying distances from the bole of the tree. In addition, we can compute the probable total surface area, in both the foliage and branchwood zones, and estimate the storage capacity of the crown by following the research done for precipitation throughfall (Grah and Wilson 1944; Hamilton and Rowe 1949; Raymond 1967; and Rutter and others 1971). Storage capacity has been defined by Grah and Wilson as the theoretical depth to which water would be retained if spread evenly over the plant surfaces. They calculated values of 0.003 and 0.007 inch, respectively, for *Pinus radiata* and *Baccharis pilularis*. Comparable values were reported by Leyton and others (1967): film thicknesses from 0.003 to 0.008 inch for grasses and some trees, and values up to 0.015 inch for bracken.

The amount of retardant retained in a tree canopy will be affected by the viscosity, cohesiveness, adhesiveness, or other rheological retardant properties, and until experimental results indicate a better value we will assume a theoretical depth (film thickness) of 0.007 inch. By applying the equations and the assumed liquid depth we can compute the retardant drop concentration that would saturate the crown. For a 50-year-old tree this was found to be 2.44 gal/100 ft^2 of ground area or 0.039 inch of liquid per square foot of projected crown area. This is less than the 0.05 inch cited by Zinke (1967) as storage capacity for rain on most grasses, shrubs, and trees. The computed value, however, is certainly within the range of observed storage capacities.

When precipitation or retardant falls, the storage capacity starts to be filled, but a certain portion of the liquid passes through the crown to the ground as throughfall. The amount of throughfall can be estimated by using equations for the crown property with the results of the retardant retention equations discussed earlier. For the foliage zone, equation (6) for polypyrolene represents the surface retention property:

$$Y = 0.264 \exp(-5.5 \times 10^{-4} \times \bar{\sigma})$$

With a mean surface area-to-volume ratio, $\bar{\sigma}$, of 1,074 ft^2/ft^3, the retardant fraction retained, Y, equals 0.125. For the branchwood zone, the white birch equation (7) represents the retention characteristic:

$$Y = 0.885 \exp(-1.83 \times 10^{-3} \times \bar{\sigma})$$

With a mean surface area-to-volume ratio of 45.3 ft^2/ft^3, the retardant fraction retained equals 0.822. The crown properties of three ages of trees are given in table 3.

These data can be combined to describe the transmission of retardant through a tree crown and the distribution on the ground. To study retardant retention by size class, we made the following assumptions: (1) The retardant is dropped from a high enough altitude so its forward velocity is zero before reaching the fuel; (2) all of the crown surface area is available to retain retardant; (3) the retardant is uniform in droplet size; and (4) attenuation is similar to that affecting radiant energy transmission. In addition, the drip-through component is not considered because the rheologic properties of retardants introduce numerous unknowns affecting drip-through. The general form of equation (3) is then reduced to:

$$C_n = C_{n-1} \exp(-\sigma\beta\ell) \qquad (23)$$

However, we refine this equation by introducing the two strata--foliage and branchwood zones--and the retardant fraction retained, Y, becomes γ_f and γ_b for each zone.

$$C_n = C_{n-1}[\exp(-\sigma_f\beta_f\ell_f\gamma_f)]\ [\exp(-\sigma_b\beta_b\ell_b\gamma_b)] \qquad (24)$$

where:

subscripts f and b refer to foliage and branchwood, respectively

σ_f and σ_b = mean surface area-to-volume ratio, ft^2/ft^3

β_f and β_b = packing ratio, dimensionless

ℓ_f and ℓ_b = distance through the zone, ft

γ_f and γ_b = retardant capture effectiveness, dimensionless.

The vertical distances through the two zones of a tree canopy can be calculated for any given radius from the bole and the other three values of the exponent for both zones are known; therefore, the fractional amount of retardant transmitted through canopies can be calculated. Figure 5 shows the distribution underneath the canopies for the trees shown in table 3. The sharp breaks occurring for the 20- and 100-year-old trees illustrate that data are lacking on the changes in weight of foliage and branchwood that occur with age and variations in thickness of the foliage zone.

The degree of agreement between the concept of transmission and the natural situation is illustrated by the comment made by Eschner (1967): "Delfs (1958) showed a pattern of throughfall under spruce increasing in the following order: mature stand, pole stand, saplings and regeneration." The distribution underneath 100-, 50-, and 20-year-old fir shown in figure 5 agrees with this observation. Results of this study can also be tested by the work of Zinke (1967) and Stout and McMahon (1961), who presented data for hardwoods and conifers in spring conditions and throughfall distribution at various distances out from the bole to the perimeter of the tree crown. The points between the bole and the perimeter were normalized by the radius of the crown, and the results obtained from this study were compared to observed values (fig. 6).

The modeling tends to predict greater interception than actually found. Since the equation for throughfall of retardant does not allow for drip-through and transport other than direct vertical fall, we would expect that there would be more retardant actually transmitted than predicted.

Table 3.--*Crown characteristics calculated for Douglas-fir at three ages*

Properties of tree	Age in years 20	 50	 100
Total height, H_T (feet)	26.2	60.6	82.8
Diameter, DBH (inches)	5.0	15.1	22.9
Crown height, h (feet)	17.1	43.4	63.4
Crown weight, W_c (pounds)	23.6	185.0	412.0
Crown width, C_w (feet)	12.2	26.6	37.6
Branchwood zone:			
Height, h' (feet)	5.9	30.3	49.9
Radius, R (feet)	2.1	9.3	14.8
Surface area-to-volume, σ (ft^2/ft^3)			
Foliage zone	1,074.0	1,074.0	1,074.0
Branchwood zone	45.3	45.3	45.3
Packing ratio, β (dimensionless)			
Foliage zone	4.5×10^{-4}	4.3×10^{-4}	4.2×10^{-4}
Branchwood zone	1.5×10^{-2}	1.1×10^{-3}	6.0×10^{-4}

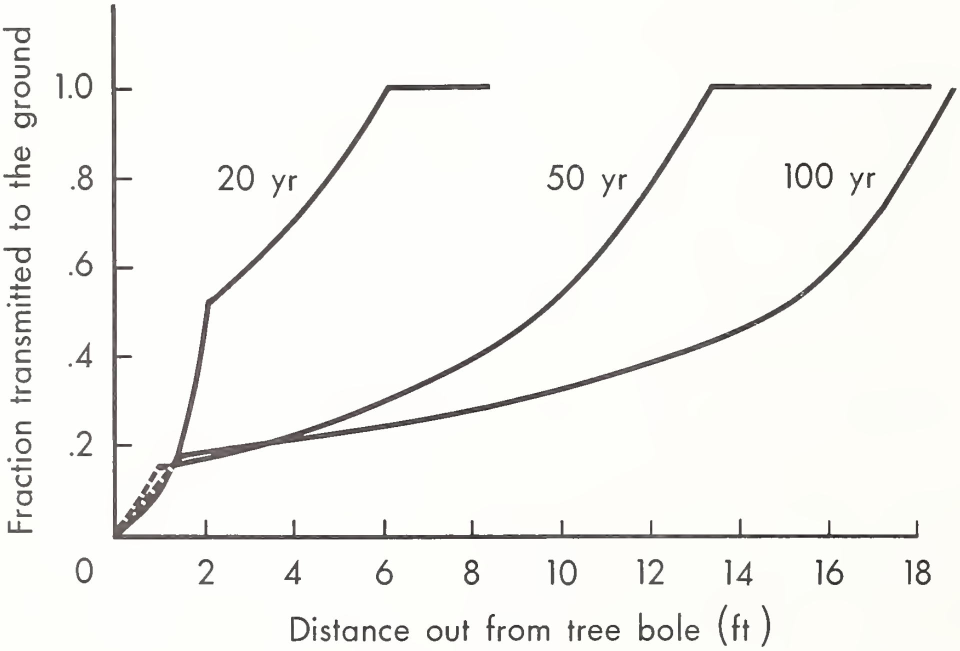

Figure 5.--Retardant transmission through crowns of trees of three different ages. Fraction reaching ground appears to become less as tree ages.

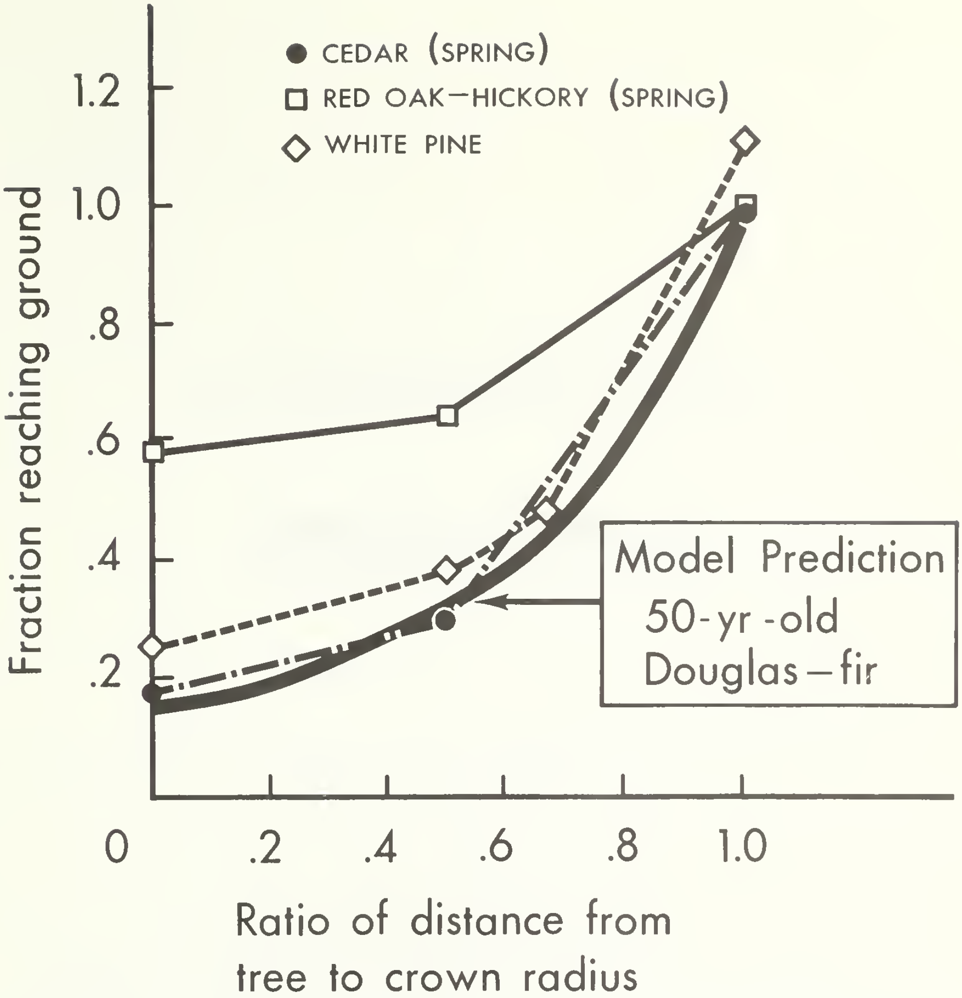

Figure 6.--Retardant throughfall predicted by modeling (Douglas-fir) compared to rain throughfall (cedar, red oak, white pine) reported by others. Fractions reaching ground are similar.

CONCLUSIONS

The results of the retardant drop tests provided equations that relate retardant retention to fuel size. In addition, the influence of surface roughness could be identified. Droplet size, which was observed to be a function of rheological properties, was not part of the study. Additional studies should be made to account for rheologic variations, such as the effects of viscosity or other rheologic properties on droplet size and spatial distribution within the retardant cloud.

Applying tree crown data has illustrated the types of distribution that can be expected under tree canopies. The results agree with recorded field observations. Results among different timber types cannot be compared until additional information is acquired on the relationships between foliage and branchwood within tree canopies for the various western conifers by age, site, and aspect. Additional work is needed to define changes in the foliage zone with age and condition of the tree. Work also is needed for stand conditions where crown data for open-grown trees do not fit.

Distribution of trees within a stand needs to be studied so we can realistically assess retardant distribution on the ground under various crown closure conditions. From this information it will be possible to estimate retardant penetration and predict degree of penetration through tree crowns. In addition, the information acquired may prove valuable to other modeling efforts such as predicting crown fires.

LITERATURE CITED

Baskerville, G. L.
1965. Estimation of dry weight of tree components and total standing crop in conifer stands. Ecology 46(6):187-189.

Bella, I. E.
1971. A new competition model for individual trees. For. Sci. 17:364-372.

Brickell, James E.
1968. A method for constructing site index curves from measurements of tree age and height--its application to Inland Douglas-fir. USDA For. Serv. Res. Pap. INT-47, 23 p., illus.

Brown, James K.
1970. Ratios of surface area to volume for common fine fuels. For. Sci. 16:101-105.

Eschner, Arthur R.
1967. Interception and soil moisture distribution. *In*: Forest Hydrology, Proc. Natl. Sci. Found. Adv. Sci. Semin., p. 191-200. Pergamon Press, New York.

Fahnestock, G. R.
1960. Logging slash flammability. USDA For. Serv. Res. Pap. INT-58, 67 p., illus.

George, Charles W.
1971. Liquids fight forest fires. Fert. Solutions 15(6):10-11, 15, 18, 21, illus.

George, Charles W., and Aylmer D. Blakely
1973. An evaluation of the drop characteristics and ground distribution patterns of forest fire retardants. USDA For. Serv. Res. Pap. INT-134, 60 p., illus.

Grah, Rudolf F., and Carl C. Wilson
1944. Some components of rainfall interception. J. For. 42:890-898.

Hamilton, E. L., and P. B. Rowe
1949. Rainfall interception by chaparral in California. Calif. State Board For., 43 p., illus.

Honer, T. G.
1971. Weight relationships in open- and forest-grown balsam fir trees, p. 65-78. Presented to Forest Biomass Working Group, IUFRO Congr., Gainesville, Fla., March 1971.

Kiil, A. D.
1967. Fuel weight tables for white spruce and lodgepole pine crowns in Alberta. Can. Dep. For. and Rural Dev., For. Br. Dep. Publ. 1196, 13 p., illus.

Leyton, L., E. R. C. Reynolds, and F. B. Thompson
1967. Rainfall interception in forest and moorland. *In*: Forest Hydrology, p. 163-178. Proc. Natl. Sci. Found. Adv. Sci. Semin., Pergamon Press, New York.

Mar:Moller, Carl
1947. The effect of thinning, age, and site on foliage increment, and loss of dry matter. J. For. 45:393-404.

Moir, W. H., and R. Francis
1972. Foliage biomass and surface area in three pinus contorta plots in Colorado. For. Sci. 18:41-45.

National Fire Protection Association
1967. Chemicals for forest fire fighting, ed. 2, 112 p., illus. National Fire Protection Association, Boston.

Raymond, Leonard E.
1967. Mathematical theory of interception. *In*: Forest Hydrology, p. 131-136. Proc. Natl. Sci. Found. Adv. Sci. Semin. Pergamon Press, New York.

Rutter, A. J., K. A. Kershaw, D. C. Robins, and A. J. Morton
1971. A predictive model of rainfall interception in forests. I. Derivation of the model from observations in a plantation of corsican pine. Agric. Meteorol. 9:367-384.

Smith, J. Harry G.
1968. Simulation of forest fuels. Northwest Sci. Assoc. Annu. Meet., For. Sect., 7 p. Central Wash. State Coll., Ellensburg.

Stephens, G. R.
1969. Foliage distribution in tree crown and stand canopy. Agric. Meteorol. 6:275-282.

Storey, T. G., W. L. Fons, and F. M. Sauer
1955. Crown characteristics of several coniferous tree species. USDA For. Serv. Div. Fire Res. Interim Rep. AFSWP-416, 95 p., illus.

Stout, Benjamin B., and Richard J. McMahon
1961. Throughfall variation under tree crowns. J. Geophys. Res. 66(6):1839-1843.

Zinke, Paul J.
1967. Forest interception studies in the United States. *In*: Forest Hydrology, p. 137-161. Proc. Natl. Sci. Found. Adv. Sci. Semin. Pergamon Press, New York.

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ANDERSON, HAL E.
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Arrays simulating wildland fuels were exposed to fire retardant cascaded from airplanes. Percentage of retardant retained was dependent on fuel element diameter and roughness. Equations were developed and were extended to field situations through research published on rainfall. Retardant transmission through a tree crown was modeled; results agreed with published findings on rainfall.

OXFORD: 432.331:431. KEYWORDS: retardant delivery, fire research, forest fuels, fuel properties, modeling.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
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